User's manual of the **Mode-Matching_3D** software package

IRCTR-S-016-03

Scientific report 2 July 2003

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Abstract

A software package for the analysis (and design) of dielectric-filled, flanged, parallel-plate waveguide antennas, is presented. For the computation of the electromagnetic field quantities, the package employs an efficient semi-analytic method, the mode-matching technique. The features of the package and the presently available post-processing capabilities are described. The possibilities for employing the software package as an educational tool are discussed.

1 Introduction

The use of the (semi-analytic) *mode-matching technique* for the analysis of dielectric-filled, flanged, parallel-plate waveguide antennas, was discussed in [1, 2, 3]. The theoretical foundations of this method were presented in [1] and [2] for the cases of the $E-$ and $H-$polarisations [4] (p. 172), respectively. The method was initially implemented for the two polarisations separately [1, 2] and, subsequently, in a computer code for their simultaneous analysis [3].

The present contribution focuses on the new version of the **Mode_matching** code, denoted as **Mode_matching_3D**, that allows the *three-dimensional* modelling of the radiating apertures of dielectric-filled, flanged waveguides. The current version of the package provides a full range of new post-processing options, specifically designed for the three-dimensional analysis that is aimed at, as well as supplementary modules for the spectral analysis of the properties of the waveguide antennas.

Like its previous, two-dimensional, version (see [3]), the **Mode_matching_3D** code was developed with an eye on the software being potentially employed as an educational tool. For meeting the speed and versatility requirements imposed by educational applications, the computational engine of the **Mode_matching_3D** package was implemented in **C**$^{++}$, while the graphic post-processing modules were implemented in MATLAB. Furthermore, new options for generating materials for presentations (e.g. "movies") were added to the package.

The theoretical background of the implemented method will be firstly sketched. Subsequently, some general information concerning the installation and the use of the software-code, as well as some examples demonstrating its new post-processing features, will be provided. This

report is completed with a "quick reference" containing the complete list of functions that are implemented in the present version of the package. For suggestions concerning the employing of the package in educational activities, the user is referred to [3].

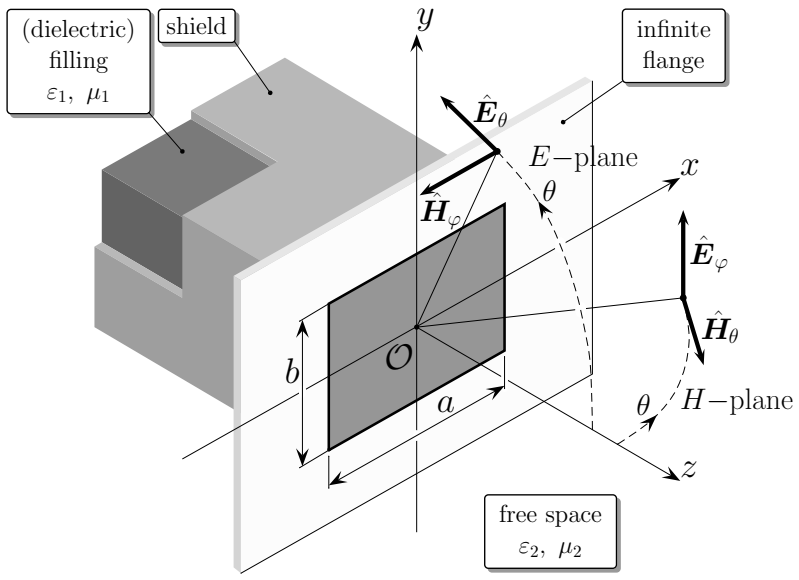

Figure 1: Dielectric-filled, flanged, rectangular waveguide antenna.

2 The analysed configurations

The **Mode_matching_3D** software package analyses the behaviour and the performances of a dielectric-filled, flanged, rectangular waveguide antenna (see Fig. 1). In this configuration, position is specified by the coordinates in a Cartesian reference frame $\mathcal{O}xyz$. For being able to express the field quantities in the far-field region, where the electromagnetic field propagates, practically, as spherical waves, a polar reference frame $\mathcal{O}r\theta\varphi$ is employed, as well. Following the usual conventions [5](p. 47), the angle θ measures the tilting of an arbitrary direction with respect to the $\mathcal{O}z$ axis, while the angle φ measures the rotation around $\mathcal{O}z$, with the $\mathcal{O}x$ axis being taken as a reference.

The sub-domain in the interior of the waveguide $\{-a/2<x<a/2\,,\ -b/2<y<b/2\,,\ -\infty<z<0\}$ (with a and b being the width and the height of the waveguide, respectively) is filled with a homogeneous, isotropic (dielectric) medium with permittivity ε_1 and permeability μ_1. The open waveguide radiates into the right half-space $\{-\infty<x<\infty\,,\ -\infty<y<\infty\,,\ 0<z<\infty\}$, where the medium is taken to be homogeneous and isotropic and it is characterised by the permittivity ε_2 and the permeability μ_2. The perfectly conductive flange extends to infinity. At any location in the investigated configuration, the electromagnetic field's state is described, in the time Laplace domain, by the electric field strength $\hat{\boldsymbol{E}}(\boldsymbol{r},\mathrm{j}\omega)$ and by the magnetic field strength $\hat{\boldsymbol{H}}(\boldsymbol{r},\mathrm{j}\omega)$, with $\boldsymbol{r}=x\boldsymbol{i}_x+y\boldsymbol{i}_y+z\boldsymbol{i}_z$ denoting the position vector, $\mathrm{j}=\sqrt{-1}$ and $\omega\geqslant 0$ denoting the angular frequency. (For simplifying the notation, the explicit mentioning of the complex $\mathrm{j}\omega$-parameter is hereafter discarded.) The rectangular waveguide is excited by means of a $\mathrm{TE}_{10}-$mode. For the chosen excitation, the electromagnetic field is characterised by an $E-$polarisation [4](p. 172)

in the $y = 0$ plane and an $H-$polarisation in the $x = 0$ plane. Employing the terminology in [5] (pp. 29–31), the $x = 0$ plane is referred to as the $E-$plane, while the $y = 0$ plane is referred to as the $H-$plane.

Assuming a spherical waves behaviour of the electromagnetic field in the far-field region, the electric field strength reads $\hat{\boldsymbol{E}} = \hat{\boldsymbol{E}}_\theta + \hat{\boldsymbol{E}}_\varphi$, with $\hat{\boldsymbol{E}}_\theta = \hat{E}_\theta \boldsymbol{i}_\theta$ and $\hat{\boldsymbol{E}}_\varphi = \hat{E}_\varphi \boldsymbol{i}_\varphi$, while the magnetic field strength reads $\hat{\boldsymbol{H}} = \hat{\boldsymbol{H}}_\theta + \hat{\boldsymbol{H}}_\varphi$, with $\hat{\boldsymbol{H}}_\theta = \hat{H}_\theta \boldsymbol{i}_\theta$ and $\hat{\boldsymbol{H}}_\varphi = \hat{H}_\varphi \boldsymbol{i}_\varphi$.

3 The mode-matching technique

3.1 Field quantities in the waveguide

The electric field strength inside the waveguide $\hat{\boldsymbol{E}}_1$ is expressed as a superposition of an infinite number of incident and reflected $TE-$ and $TM-$waves (modes) [6]. In view of the excitation being an $\hat{E}_y$ component with an "even-even" $x \leftrightarrow y$ symmetry, the following choice of modes is employed for expressing the transverse components of $\hat{\boldsymbol{E}}_1$:

- $TE-$ and $TM-$modes displaying an "odd-odd" $x \leftrightarrow y$ symmetry in the case of the $\hat{E}_{1;x}$ component and
- $TE-$ and $TM-$modes displaying an "even-even" $x \leftrightarrow y$ symmetry in the case of the $\hat{E}_{1;y}$ component.

With these choices, the relevant components read:

$$\begin{aligned}
\hat{E}_{1;x} = \quad & \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \Big\{ A_{mn}^{(\mathrm{TE})}\, k_n\, \sin(k_m\, x) \sin(k_n\, y) \\
& \qquad \Big[\hat{V}_{mn}^{(\mathrm{TE};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) + \hat{V}_{mn}^{(\mathrm{TE};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\} \\
& - \sum_{i=0}^{\infty}\sum_{j=1}^{\infty} \Big\{ A_{mn}^{(\mathrm{TM})}\, k_m\, \sin(k_m\, x) \sin(k_n\, y) \\
& \qquad \Big[\hat{V}_{mn}^{(\mathrm{TM};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) + \hat{V}_{mn}^{(\mathrm{TM};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\}, \qquad (1) \\
\hat{E}_{1;y} = \quad & \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \Big\{ A_{mn}^{(\mathrm{TE})}\, k_m\, \cos(k_m\, x) \cos(k_n\, y) \\
& \qquad \Big[\hat{V}_{mn}^{(\mathrm{TE};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) + \hat{V}_{mn}^{(\mathrm{TE};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\} \\
& + \sum_{i=0}^{\infty}\sum_{j=1}^{\infty} \Big\{ A_{mn}^{(\mathrm{TM})}\, k_n\, \cos(k_m\, x) \cos(k_n\, y) \\
& \qquad \Big[\hat{V}_{mn}^{(\mathrm{TM};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) + \hat{V}_{mn}^{(\mathrm{TM};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\}, \qquad (2)
\end{aligned}$$

where

$m = 2i + 1$ and $n = 2j$ $(i, j = 0, 1, \ldots)$,

$k_m = m\,\pi/a$ $(m = 1, 3, 5, \ldots)$ and $k_n = n\,\pi/b$ $(n = 0, 2, 4, \ldots)$ denote the transverse modal wave numbers,

$A_{mn}^{(\mathrm{TE})}$ $(m = 1, 3, 5, \ldots$ and $n = 0, 2, 4, \ldots)$ and $A_{mn}^{(\mathrm{TM})}$ $(m = 1, 3, 5, \ldots$ and $n = 2, 4, \ldots)$ denote some constants having the expressions:

$$A_{mn}^{(\mathrm{TE})} = \begin{cases} (2/ab)^{1/2}/k_{c;mn} & \text{for } n = 0 \\ (4/ab)^{1/2}/k_{c;mn} & \text{otherwise} \end{cases} \tag{3}$$

$$A_{mn}^{(\mathrm{TM})} = (4/ab)^{1/2}/k_{c;mn}, \tag{4}$$

with $k_{c;mn} = \left(k_m^2 + k_n^2\right)^{1/2}$ being the cutoff wave number,

$\hat{V}_{mn}^{(\mathrm{TE};+)}$ and $\hat{V}_{mn}^{(\mathrm{TE};-)}$ $(m = 1, 3, 5, \ldots$ and $n = 0, 2, 4, \ldots)$ denote the modal amplitudes of the incident and reflected $TE-$modes, respectively,

$\hat{V}_{mn}^{(\mathrm{TM};+)}$ and $\hat{V}_{mn}^{(\mathrm{TM};-)}$ $(m = 1, 3, 5, \ldots$ and $n = 2, 4, \ldots)$ denote the modal amplitudes of the incident and reflected $TM-$modes, respectively and

$\hat{\beta}_{mn} = \left(k_1^2 - k_{c;mn}^2\right)^{1/2}$ denotes the propagation coefficient in the waveguide, with $k_1 = \omega\left(\varepsilon_1\mu_1\right)^{1/2}$ being the wave number in the waveguide; note that, in view of ensuring the causality, $\Re\{\hat{\beta}_{mn}\} \geqslant 0$ and $\Im\{\hat{\beta}_{mn}\} \leqslant 0$.

Correspondingly, the transverse components of $\hat{\boldsymbol{H}}_1$ in the waveguide follow as:

$$\begin{aligned} \hat{H}_{1;x} = &- \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \Big\{ \hat{Y}_{z;mn}^{(\mathrm{TE})}\; A_{mn}^{(\mathrm{TE})}\, k_m\, \cos\left(k_m\, x\right) \cos\left(k_n\, y\right) \\ &\qquad \Big[\hat{V}_{mn}^{(\mathrm{TE};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) - \hat{V}_{mn}^{(\mathrm{TE};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\} \\ &- \sum_{i=0}^{\infty}\sum_{j=1}^{\infty} \Big\{ \hat{Y}_{z;mn}^{(\mathrm{TM})}\; A_{mn}^{(\mathrm{TM})}\, k_n\, \cos\left(k_m\, x\right) \cos\left(k_n\, y\right) \\ &\qquad \Big[\hat{V}_{mn}^{(\mathrm{TM};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) - \hat{V}_{mn}^{(\mathrm{TM};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\}, \end{aligned} \tag{5}$$

$$\begin{aligned} \hat{H}_{1;y} = &\sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \Big\{ \hat{Y}_{z;mn}^{(\mathrm{TE})}\; A_{mn}^{(\mathrm{TE})}\, k_n\, \sin\left(k_m\, x\right) \sin\left(k_n\, y\right) \\ &\qquad \Big[\hat{V}_{mn}^{(\mathrm{TE};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) - \hat{V}_{mn}^{(\mathrm{TE};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\} \\ &- \sum_{i=0}^{\infty}\sum_{j=1}^{\infty} \Big\{ \hat{Y}_{z;mn}^{(\mathrm{TM})}\; A_{mn}^{(\mathrm{TM})}\, k_m\, \sin\left(k_m\, x\right) \sin\left(k_n\, y\right) \\ &\qquad \Big[\hat{V}_{mn}^{(\mathrm{TM};+)}\, \exp(-\mathrm{j}\hat{\beta}_{mn} z) - \hat{V}_{mn}^{(\mathrm{TM};-)}\, \exp(\mathrm{j}\hat{\beta}_{mn} z) \Big] \Big\}, \end{aligned} \tag{6}$$

where the longitudinal wave impedances $\hat{Y}^{(\mathrm{TE})}_{z;mn}$ ($m = 1, 3, 5, \ldots$ and $n = 0, 2, 4, \ldots$) and $\hat{Y}^{(\mathrm{TM})}_{z;mn}$ ($m = 1, 3, 5, \ldots$ and $n = 2, 4, \ldots$) have the expressions:

$$\hat{Y}^{(\mathrm{TE})}_{z;mn} = \hat{\beta}_{mn}/(\omega\mu_1), \tag{7}$$

$$\hat{Y}^{(\mathrm{TM})}_{z;mn} = (\omega\varepsilon_1)/\hat{\beta}_{mn}. \tag{8}$$

As for the longitudinal components of the field quantities $\hat{\boldsymbol{E}}_1$ and $\hat{\boldsymbol{H}}_1$ are concerned, they follow directly by employing the strategy indicated in [6](pp. 3–10)

3.2 Aperture continuity requirements and boundary conditions at the flanges

The continuity of the tangential components of the electric and of the magnetic field strengths at the aperture requires

$$\lim_{z\uparrow 0} \hat{E}_{1;x} = \lim_{z\downarrow 0} \hat{E}_{2;x} \quad \text{for } |x| < a/2 \text{ and } |y| < b/2, \tag{9}$$

$$\lim_{z\uparrow 0} \hat{E}_{1;y} = \lim_{z\downarrow 0} \hat{E}_{2;y} \quad \text{for } |x| < a/2 \text{ and } |y| < b/2, \tag{10}$$

$$\lim_{z\uparrow 0} \hat{H}_{1;x} = \lim_{z\downarrow 0} \hat{H}_{2;x} \quad \text{for } |x| < a/2 \text{ and } |y| < b/2, \tag{11}$$

$$\lim_{z\uparrow 0} \hat{H}_{1;y} = \lim_{z\downarrow 0} \hat{H}_{2;y} \quad \text{for } |x| < a/2 \text{ and } |y| < b/2. \tag{12}$$

The boundary conditions at the perfectly conducting flanges are

$$\lim_{z\downarrow 0} \hat{E}_{2;x} = 0 \quad \text{for } |x| > a/2 \text{ and } |y| > b/2, \tag{13}$$

$$\lim_{z\downarrow 0} \hat{E}_{2;y} = 0 \quad \text{for } |x| > a/2 \text{ and } |y| > b/2. \tag{14}$$

3.3 Field quantities in the right half-space

Integral representations of the field quantities

A first possibility of expressing the field quantities in the right half-space is by employing their Helmholtz integral representations in terms of the values of the electric field strength's components $\hat{E}_x$ and $\hat{E}_y$ at the aperture (see [5, 7]). The relevant expressions are amenable to a direct (numerical) evaluation, thus providing the values of all the components of the field quantities in the right half-space.

Fourier representations of the field quantities

For the computation of the modal expansion coefficients, an alternative, more adequate, representation of the field quantities, based on a spatial Fourier representation, will be employed.

For the derivation of the relevant representations of the field quantities it is firstly observed that the field in the right half-space corresponds to a field propagating in an unbounded domain. Based on the "odd-odd" $x \leftrightarrow y$ symmetry of the $\hat{E}_{1;x}$ component inside the waveguide, the quantity $\hat{E}_{2;x}$ is expressed in terms of the inverse Fourier transform of a yet to be determined

function $\hat{B}_2^{\mathrm{odd}}(\alpha,\beta)$, the function $\hat{B}_2^{\mathrm{odd}}(\alpha,\beta)$ showing an "odd-odd" symmetry, as well. The representation is then written as

$$\hat{E}_{2;x} = -\frac{1}{\pi^2}\int_0^\infty\int_0^\infty \left[\hat{B}_2^{\mathrm{odd}}(\alpha,\beta)\ \sin(\alpha x)\sin(\beta y)\ \exp\left(\mathrm{j}\hat{\Gamma}z\right)\right]\mathrm{d}\alpha\,\mathrm{d}\beta, \tag{15}$$

where $\hat{\Gamma} = \left[k_2^2 - \left(\alpha^2+\beta^2\right)\right]^{1/2}$ denotes the propagation coefficient, with $k_2 = \omega\left(\varepsilon_2\mu_2\right)^{1/2}$ being the wave number in the right half-space. Note that, in view of ensuring the causality, $\Re\{\hat{\Gamma}\} \geqslant 0$ and $\Im\{\hat{\Gamma}\} \leqslant 0$. Similarily, based on the "even-even" $x \leftrightarrow y$ symmetry of the $\hat{E}_{1;y}$ component inside the waveguide, the quantity $\hat{E}_{2;y}$ is expressed in terms of the inverse Fourier transform of a yet to be determined function $\hat{B}_2^{\mathrm{even}}(\alpha,\beta)$ showing an "even-even" symmetry

$$\hat{E}_{2;y} = \frac{1}{\pi^2}\int_0^\infty\int_0^\infty \left[\hat{B}_2^{\mathrm{even}}(\alpha,\beta)\ \cos(\alpha x)\cos(\beta y)\ \exp\left(\mathrm{j}\hat{\Gamma}z\right)\right]\mathrm{d}\alpha\,\mathrm{d}\beta. \tag{16}$$

By using the formalism described in [5](p. 623), (15) and (16) yield the values of the magnetic field strength in the right half-space, that read

$$\hat{H}_{2;x} = -\frac{1}{\omega\mu_2}\frac{1}{\pi^2}\int_0^\infty\int_0^\infty \left\{\left[\frac{\beta^2+\hat{\Gamma}^2}{\hat{\Gamma}}\hat{B}_2^{\mathrm{even}}(\alpha,\beta) + \frac{\alpha\beta}{\hat{\Gamma}}\hat{B}_2^{\mathrm{odd}}(\alpha,\beta)\right] \cos(\alpha x)\cos(\beta y)\ \exp\left(\mathrm{j}\hat{\Gamma}z\right)\right\}\mathrm{d}\alpha\,\mathrm{d}\beta \tag{17}$$

$$\hat{H}_{2;y} = -\frac{1}{\omega\mu_2}\frac{1}{\pi^2}\int_0^\infty\int_0^\infty \left\{\left[\frac{\alpha^2+\hat{\Gamma}^2}{\hat{\Gamma}}\hat{B}_2^{\mathrm{odd}}(\alpha,\beta) + \frac{\alpha\beta}{\hat{\Gamma}}\hat{B}_2^{\mathrm{even}}(\alpha,\beta)\right] \sin(\alpha x)\sin(\beta y)\ \exp\left(\mathrm{j}\hat{\Gamma}z\right)\right\}\mathrm{d}\alpha\,\mathrm{d}\beta \tag{18}$$

3.4 Computation of the modal expansion coefficients

For determining the modal expansion coefficients, (1) and (2) are firstly equated to (15) and (16), respectively, by means of the interface boundary conditions in (9) and (10) and of the boundary conditions at the perfectly conducting flanges in (13) and (14). A direct Fourier transform of the thus obtained equations then yields the expressions of the functions $\hat{B}_2^{\mathrm{odd}}(\alpha,\beta)$ and $\hat{B}_2^{\mathrm{even}}(\alpha,\beta)$. These expressions are subsequently filled in two equations relating (5) and (6), on one hand, and (17) and (18), on the other hand, by means of the interface boundary conditions in (11) and (12). Finally, a Galerkin procedure is applied to these two equations that result into an (infinitely dimensional) linear mapping between the modal amplitudes corresponding to the incident and reflected waves.

For reasons of convenience, the double indices $\{mn\}$ of the $TE-$ and $TM-$ modes are reduced to one (l), by ordering the modes according to their increasing cutoff frequency [8]. The field expansions in the waveguide are truncated to a finite number of modes $N_{\max} = N_{\max}^{(\mathrm{TE})} + N_{\max}^{(\mathrm{TM})}$, this procedure translating the previously obtained mapping into a system of linear, algebraic equations. By assuming that the incident waves have known (impressed) amplitudes, this system directly provides the values of the unknown reflected wave amplitudes.

From a computational point of view, the most expensive operation is the determining of the entries in the system's matrix (the scattering matrix). For obtaining the values of these coefficients, double "infinite" integrals, that contain an integrable singularity, as well, need being evaluated. The difficulties arising from the presence of the integrable singularities are circumvented by applying a procedure that was described in [2]. As for the "infinite" part of the integrals is concerned, it is noted that, in view of the relevant integrands presenting a high convergence rate for large values of the integration variables, the numerical integration schemes can be stopped at acceptably low values of these variables, without a detrimental effect on the accuracy of the computed integrals.

4 General description of the software package

The mode-matching technique for the analysis of dielectric-filled, flanged waveguide antennas described in Section 3 was implemented in a software package named **Mode_matching_3D**. The configuration examined by the software package was illustrated in Fig. 1. The main component of the package is the stand-alone, executable, **Microsoft Windows** compatible program **Mode_matching_3D**. The computational engine of the package is implemented in **C**$^{++}$ [9]. The graphical post-processing options employ the MATLAB engine [10] and a collection of "M-files" [10] that need being available on the computer on which the program runs. The executable can run independently, as well, in which case the graphical post-processing are disabled. Note that for taking advantage of all currently implemented post-processing options, MATLAB version 6.0 is required. Nevertheless, most graphical post-processing modules will also run under MATLAB version 5.3.

4.1 Installation of the software package

The present implementation of the **Mode_matching_3D** software package assumes for the installation of the program the *minimal* directory tree-structure indicated in Fig. 2. The location of the "home directory" can be chosen arbitrarily. Note that the user may choose to add to the indicated tree-structure additional directories she or he considers to be necessary, but the minimal tree-structure, *with the specified names*, is mandatory for a correct run of the program.

The following actions need being carried out during the installation of the package:

- the minimal directory tree-structure must be created;
- the `Mode_matching_3D.exe` file must be copied into the directory $<$`home_directory`$>$\`bin` and *this directory must be added to the system's* `PATH` *variable*;
- the MATLAB modules pertaining to the package must be copied into the directory $<$`home_directory`$>$\`Matlab_modules` and
- the default input data file (see Section 4.3) `Mode_matching.dat` must be copied into the directory $<$`home_directory`$>$\`input`.

As for the directories $<$`home_directory`$>$\`output` and $<$`home_directory`$>$\`Matlab_movies`, they are used by the program itself for saving output data and post-processing files. Note that all user-written input data files must also be located in the directory $<$`home_directory`$>$\`input`.

```
<home_directory>\ bin\ Mode_matching_3D.exe
                 input\ Mode_matching_3D.dat [+ user-written input data files]
                 Matlab_modules\ MATLAB "M" – files
                 Matlab_movies\ [output "movie" files]
                 output\ [output data files]
```

Figure 2: The required directory tree-structure for the installation of the **Mode_matching_3D** software package

4.2 Utilisation of the software package

The utilisation of the **Mode_matching_3D** software package is illustrated for the case when the program runs in a **Microsoft Windows** command window. For starting the program, the following command must be issued:

```
Mode_matching_3D [ File_Name ]
```

The optional parameter `File_Name` denotes the name of a user-written input data file. In the case when this parameter is not specified, the default input data file `Mode_matching_3D.dat` will be employed. Since the software package is designed to work in *batch mode*, the input data file is processed by the package *without* requiring any further input on behalf of the user except, possibly, for some minimal keyboard input during the previewing of "movies" (see below).

4.3 Input data

All input data required by the program are included in an *input data file*, which is a standard ASCII file, containing *keywords*, *parameters* and, possibly, *comments*. A complete list of the keywords recognised by the current version of the **Mode_matching_3D** software package, together with the pertaining (numerical) parameters, is provided in the "quick reference" included in Appendix A. The (user-written) input data files must be located in the directory `<home_directory>\input`. At installation, the default input data file `Mode_matching_3D.dat` is copied into this directory. The user may choose to modify the contents of this file in accordance with her or his requirements or write her or his own input data files. Recall that in the case when user-written input data files are employed, the name of these files must be specified on the command line.

The following data can be prescribed by the user:

- The number of excited $TE-$ and $TM-$modes and their complex amplitude values. In the case when no such information is explicitly provided, the program assumes the standard excitation, namely by means of a $TE_{10}-$mode of unit amplitude. Note that attempting to excite the configuration by means of an evanescent mode will be signaled as an error.
- The frequency of the first prescribed $TE-$mode (the $TE_{10}-$mode in the case of the default excitation), hereafter referred to as the *fundamental mode* (of operation).
- The width a and the height b of the waveguide (see Fig. 1).

```
% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
%
%                        PROBLEM DATA
%
% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

% ..................................................................
% The choice for modes to be evaluated
%
%  - the minimum number of evaluated modes,
%  - the lower limit of the highest cutoff frequency in the
%    modal analysis
% ..................................................................

   Minimum no of modes
      6

   Minimum highest cutoff
      20e9

% ..................................................................
% The dimensions of the waveguide
% ..................................................................

   width
      0.022

   height
      0.010

% ..................................................................
% Relative material parameters inside the waveguide
% ..................................................................

   filling
      1.0                       % \mu_r_1
      1.0                       % \eps_r_1

% ..................................................................
% Relative material parameters outside the waveguide
% ..................................................................

   embedding
      1.0                       % \mu_r_2
      1.0                       % \eps_r_2

% ..................................................................
% The frequency of the fundamental excited mode (TE_{10})
% ..................................................................

   frequency
      10e9
```

```
% ..................................................................
% Infinite integrals parameter
% ..................................................................

   Truncation error at infinity
      1e-6                      % single frequency analysis
%      5e-6                      % spectral analysis

% ..................................................................
% Define the data for the "spectral analysis"
%
%  - low_frequency  high_frequency
%
%  - the number of frequencies where the spectrum is sampled
%
%  - the type of steps decreasing / constant / increasing(default)
% ..................................................................

% ..................................................................
% Define the data for the spectral analysis
%  NOTE: activated in the case of the spectral analysis, only
% ..................................................................

   spectral frequency range   % low_frequency  high_frequency
      7.51e9  40e9

   spectral sampling frequencies
      200                       % the number of samplig frequencies
                                % at which the spectrum is sampled
   constant sampling steps

% ..................................................................
% Validate the "spectral analysis"
% ..................................................................

%   Do spectral analysis

% ..................................................................
% Output data files
% ..................................................................

   solution file name
      Demo_solution

   spectral solution file name
      Demo_s_a_solution

% ..................................................................
% The run type controlling flag
% ..................................................................
   Run Type
      2
```

Figure 3: Example of an input data file (problem description part).

Note that the user has the option to prescribe either the width of the waveguide or the frequency and to instruct the code to compute the complementary parameter (i.e. the frequency or the width, respectively) such that the width of the waveguide equals a *user specified quotient from the wavelength of the fundamental mode*.

- The material parameters of the medium inside the waveguide, i.e. the *relative* permittivity $\varepsilon_{1;\mathrm{r}}$ and the *relative* permeability $\mu_{1;\mathrm{r}}$.
- The material parameters of the medium in the right-hand half-space, i.e. the *relative* permittivity $\varepsilon_{2;\mathrm{r}}$ and the *relative* permeability $\mu_{2;\mathrm{r}}$.
- Parameters required for carrying out the spectral analysis (for example, the upper and lower bounds of the analysed frequency range and the distribution of the sampling frequencies over that range).
- The names of the files in which output data are saved.

Since the code performs the check on the consistency of the input data only after the complete set of parameters defining the problem at hand have been read, the sequence in which the various parameters are input is arbitrary. Note that there is a number of parameters that are of relevance for the spectral analysis of the open waveguide, only (see Section 4.6).

The **Mode_matching_3D** program can operate in *four* different runtime modes. The choice between these modes is done by means of a control variable, denoted as Run_Type, that can have any of the following values:

Run_Type = 1 (default value)

The program is run for solving a new problem and no post-processing tasks are executed (this case is hereafter referred to as the "solving a new problem, only" – mode).

Run_Type = 2

The program is run for solving a new problem and post-processing the computed data (this case is hereafter referred to as the "solving a new problem and post-processing" – mode).

Run_Type = 3

The program is run for post-processing the computed data pertaining to a previously solved problem (this case is hereafter referred to as the "post-processing, only" – mode).

Run_Type = 4

The program displays the complete list of $TE-$ and $TM-$modes that are accounted for, with their pertaining cutoff frequencies; no processing of the input data is performed (this case is hereafter referred to as the "mode-displaying, only" – mode).

```
% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
%
%                        POST PROCESSING
%
% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

   POST PROCESSING

% ..................................................................
% Plot parameters
% ..................................................................

   plot angle
      1

   shading type
      1

   font sizes
      18   14

   display text
      0

   aperture distribution step ratio
      1.05

% ..................................................................
% Post-processing tasks / standard run
% ..................................................................

   Compute directivity
      0 0

   Compute TL-parameters TE_10

% ..................................................................
% End of post-processing / standard run
% ..................................................................

   END

% ..................................................................
% Spectral analysis post-processing commands
% ..................................................................

   POST PROCESS / SPECTRAL ANALYSIS

% ..................................................................
% Spectral analysis specific plot parameters
% ..................................................................

   unchanged hardcopy

% ..................................................................
% Post-processing tasks / spectral analysis
% ..................................................................

   plot S_11 TE_10

% ..................................................................
% End of post-processing / spectral analysis
% ..................................................................

   END
```

Figure 4: Example of an input data file (post-processing part).

By default, the **Mode_matching_3D** program runs in the "post-processing, only" – mode. The user can override this default setting by giving the Run_Type parameter a value in the input data file (see Appendix A).

```
                Mode-matching / three dimensional analysis
                (c) 2003 by Delft University of Technology

            Output generated on Tue Jun 24, 2003 at 15:55:03

The problem's definition:

(The problem's data is read from the file
D:\Lager\Cpp\Mode_matching_3D\input\Mode_matching_man.dat)

   EVALUATED MODES:

TE-modes

Crt.No.     Modal indices     Cutoff frequency

1           1 , 0               6.813 GHz          propagating mode
2           3 , 0              20.440 GHz          evanescent mode
3           1 , 2              30.744 GHz          evanescent mode
4           5 , 0              34.067 GHz          evanescent mode
5           3 , 2              36.284 GHz          evanescent mode
6           5 , 2              45.380 GHz          evanescent mode

TM-modes

Crt.No.     Modal indices     Cutoff frequency

1           1 , 2              30.744 GHz          evanescent mode
2           3 , 2              36.284 GHz          evanescent mode
3           5 , 2              45.380 GHz          evanescent mode
```

Figure 5: The console output corresponding to the input data file presented in Figs. 3 and 4 (information concerning the evaluated modes part).

4.4 Output data

The output of the program consists of:

- numerical data that are directly displayed at the system's console or in "Results"–type windows (see Fig. 6).
- various types of Matlab plots and/or "movies" [11].

Results
The directivity of the radiating aperture at theta = 0° and phi = 0° is 6.4 dB.
OK
Results
The transmission-line parameters corresponding to the propagating TE_{ 1 , 0 } mode have the values:
- abs(S_{11}) = -12dB
- arg(S_{11}) = -77°
- VSWR = 1.6
OK
- The waveguide is excited by means of a TE_{10} mode of unit amplitude
- The frequency of the fundamental mode is: 10.0000 GHz
- The dimensions of the waveguide are:
- the width (a) = 22.0000 mm (0.7338 * wavelength)
- the height (b) = 10.0000 mm (0.3336 * wavelength)
- The relative material parameters inside the waveguide are:
- the relative permeability = 1.0000
- the relative permittivity = 1.0000
- The relative material parameters outside the waveguide are:
- the relative permeability = 1.0000
- the relative permittivity = 1.0000
- The problem's solution will be stored in the file D:\Lager\Cpp\Mode_matching_3D\output\Demo_solution.sol
>>>> The input data describe a valid problem
Solving a (new) problem.
The computed results are also post-processed
>>>> Total time required for solving the problem: 0.6400 seconds
Post-processing the numerical results
>>>> End of post-processing

Figure 6: The console output corresponding to the input data file presented in Figs. 3 and 4 (problem description + post-processing part) and the pertaining numerical results.

4.5 Example of using the package for a single frequency analysis

The use of the **Mode_matching_3D** software for performing a *single frequency analysis* of a waveguide is demonstrated by solving a problem concerning a configuration having the following parameters:

- the width $a = 22\,\text{mm}$,
- the height $b = 10\,\text{mm}$,
- the waveguide is taken to be empty and
- the prescribed frequency of the fundamental mode is 10 GHz.

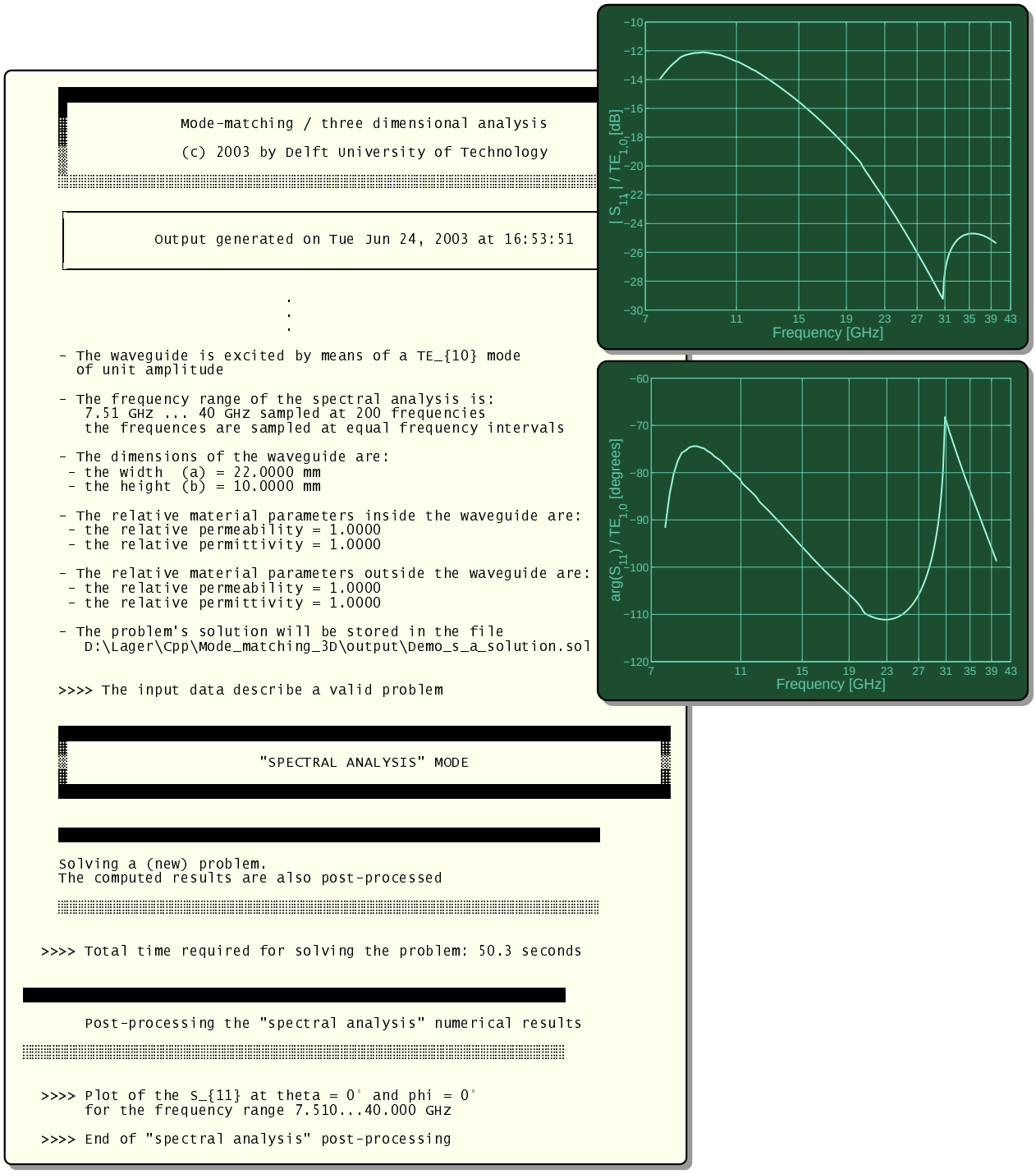
Mode-matching / three dimensional analysis
(c) 2003 by Delft University of Technology
Output generated on Tue Jun 24, 2003 at 16:53:51
- The waveguide is excited by means of a TE_{10} mode of unit amplitude
- The frequency range of the spectral analysis is: 7.51 GHz ... 40 GHz sampled at 200 frequencies the frequences are sampled at equal frequency intervals
- The dimensions of the waveguide are:
- the width (a) = 22.0000 mm
- the height (b) = 10.0000 mm
- The relative material parameters inside the waveguide are:
- the relative permeability = 1.0000
- the relative permittivity = 1.0000
- The relative material parameters outside the waveguide are:
- the relative permeability = 1.0000
- the relative permittivity = 1.0000
- The problem's solution will be stored in the file D:\Lager\Cpp\Mode_matching_3D\output\Demo_s_a_solution.sol
>>>> The input data describe a valid problem
"SPECTRAL ANALYSIS" MODE
Solving a (new) problem.
The computed results are also post-processed
>>>> Total time required for solving the problem: 50.3 seconds
Post-processing the "spectral analysis" numerical results
>>>> Plot of the S_{11} at theta = 0° and phi = 0° for the frequency range 7.510...40.000 GHz
>>>> End of "spectral analysis" post-processing
|S11| / TE1,0 [dB]
Frequency [GHz]
arg(S11) / TE1,0 [degrees]
Frequency [GHz]

Figure 7: The console output corresponding to the spectral analysis part included in the input data file presented in Figs. 3 and 4 and the pertaining numerical results: the magnitude and the phase of the S_{11} parameter in the case of the $TE_{10}-$mode.

The input data file corresponding to this configuration is presented in Figs. 3 (problem description part) and 4 (post-processing part). For the significance of the various input commands, the user is referred to the "quick reference" included in Appendix A. Note that this file also con-

tains some commands employed for prescribing parameters that are of relevance for the *spectral analysis* of the open waveguide. In this manner, the input data file can be reused for carrying out a spectral analysis, by simply un-commenting the commands that switch the program over to the relevant mode.

Firstly, the program reads the input data file and the successfully read data are echoed to the system's console (see Fig. 6). In the case when all data have been successfully read, the program proceeds to solving the (new) problem (note that Run_Type = 2). After the completion of the computation, the elapsed time is displayed and the computed data are saved in the user-specified file. Subsequently, since the program was instructed to run in the "solving a new problem and post-processing" – mode, the computed data are post-processed. The input data file presented in Fig. 4 contains console oriented post-processing commands, only, the relevant output being illustrated in Fig. 6. For the various types of plots that can be generated by means of the **Mode_matching_3D** package, the reader is referred to the "quick reference" included in Appendix A. Note that a wide variety of examples of this kind of plots can be found in [1, 2, 3]. Additionally, examples demonstrating the new post-processing features implemented in the **Mode_matching_3D** package are provided in Section 4.7.

4.6 Spectral analysis of the radiation properties of the open waveguide

For investigating the frequency behaviour of some of the open waveguide's parameters, the **Mode_matching_3D** was endowed with a *spectral analysis module*. This module repeatedly solves a problem concerning a specified configuration at a number of user-defined frequencies of the fundamental mode. For carrying out such an analysis, the user is required to specify a *frequency range* and a *number of samples* that need being evaluated. The samples can be either *equally spaced* along the indicated frequency range (default choice) or can be chosen at an *increasing* or *decreasing logarithmic* division of that range, the minimum step being, in this case, specified by the user. The computed data are then saved in an output file that can be subsequently used as input for various post-processing tasks.

Since the implementation of the spectral analysis part is based on reusing the standard modules of the **Mode_matching_3D** code, the format of the required input and output data is similar to that discussed in Sections 4.3 and 4.4. For activating this module, it is sufficient to include a number of specific commands (see Section A.4) in any valid **Mode_matching_3D** compliant input data file. For example, by un-commenting the command `Do spectral analysis` in the input file illustrated in Fig. 3, the spectral analysis will be activated in the "solving a new problem and post-processing" – mode. The investigated configuration will be identical. In view of reducing the computation time, a lower accuracy for the evaluation of the "infinite" integrals can be prescribed in this case, with negligible influence on the accuracy of the computed results. To this end, the line `1e-6` pertaining to the command `Truncation error at infinity` should be commented out and the subsequent line, reading `5e-6`, should be un-commented. The specific frequency behaviour parameters are provided by the commands:

```
spectral frequency range
   7.51e9  40e9
spectral sampling frequencies
   200
constant sampling steps
```

indicating that the spectral analysis will be performed for the frequency range $7.51, \ldots, 40\,\mathrm{GHz}$, sampled at 200 equally spaced frequencies. The console output for a run in which a new problem is solved, as well as the pertaining computed results, are presented in Fig. 7.

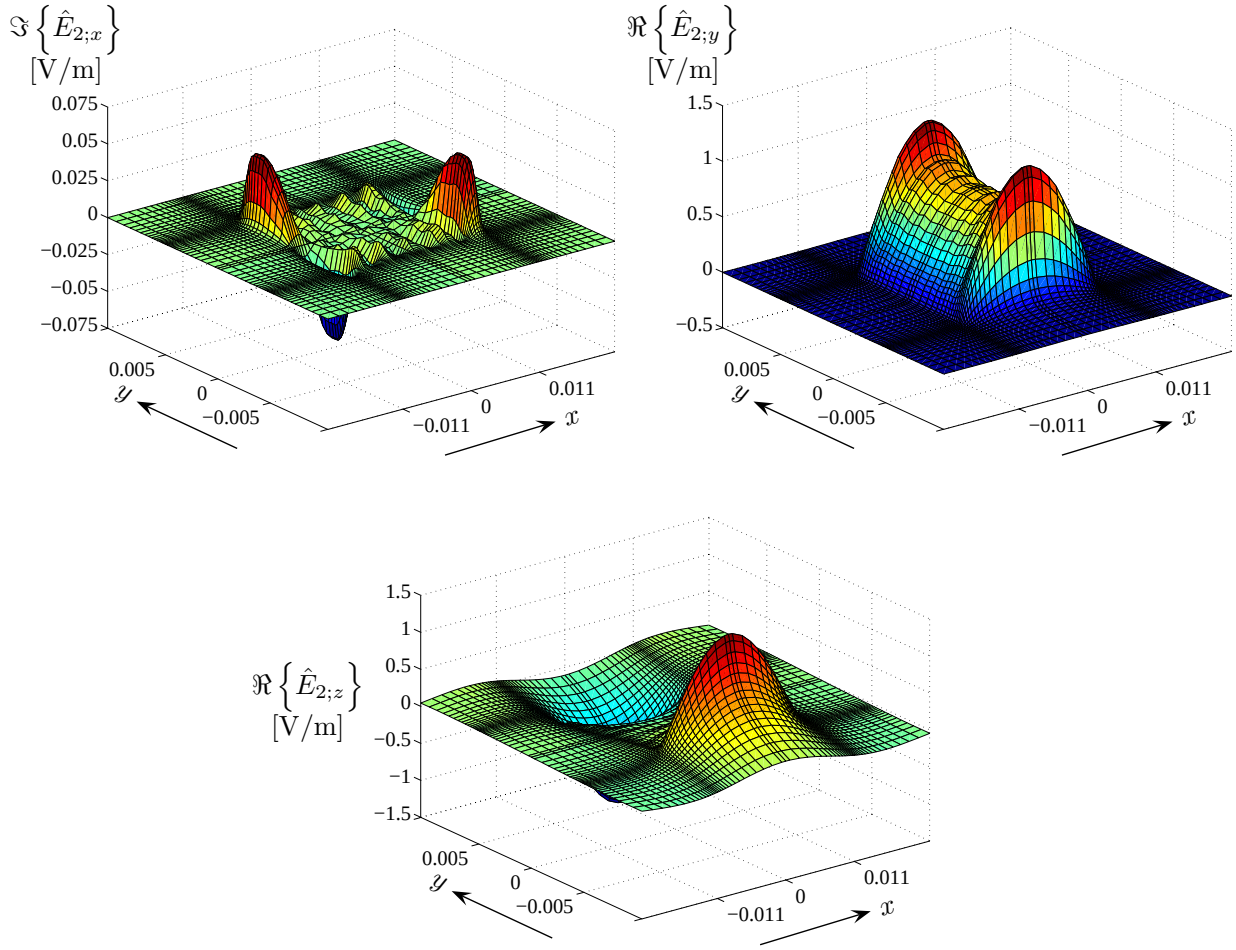

Figure 8: The distribution of the $\hat{E}_{2;x}$, $\hat{E}_{2;y}$ and $\hat{E}_{2;z}$ quantities in the plane $z = 2.2\,10^{-4}\mathrm{m}$.

4.7 New post-processing features of the Mode_matching_3D package

Since the **Mode_matching_3D** package was developed for the three-dimensional analysis of the radiation properties of the waveguide antennas, the range of (graphic) post-processing features implemented in the previous versions of the code needed being augmented with ones specifically designed for the new class of investigated problems. A number of examples of the use of these new features are hereafter given for the case of the configuration analysed in Section 4.5.

Microsoft Windows oriented displaying of numerical results

Unlike the previous versions of this software, the **Mode_matching_3D** package uses a **Microsoft Windows** compatible "message box" system for displaying numerical data as directivity, gain, etc. (see Fig. 6). In this manner, situations when these data are lost due to the scrolling of the console window are prevented.

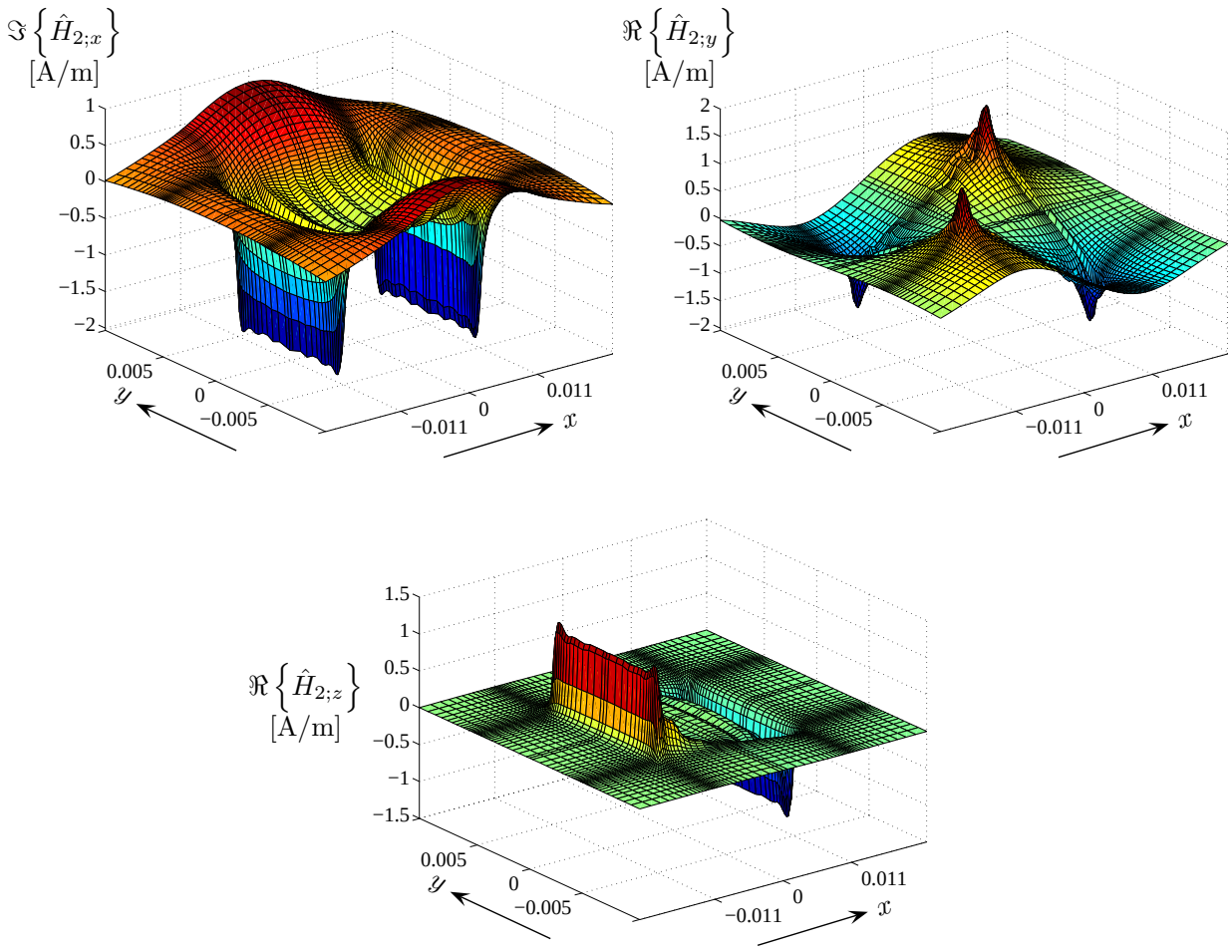

Figure 9: The distribution of the $\hat{H}_{2;x}$, $\hat{H}_{2;y}$ and $\hat{H}_{2;z}$ quantities in the plane $z = 2.2\,10^{-4}$m.

Evaluation of the transmission line parameters of waveguide antennas

The **Mode_matching_3D** package implements, for the first time, facilities for computing some transmission line parameters of waveguide antennas such as the $S-$parameters and the *voltage standing wave ratio (VSWR)* [5]. These parameters can be computed both for single frequency and for spectral analyses, an example for the latter case being provided in Fig. 7.

Analysis of the field quantities at $z =$ constant planes

The previous versions of the **Mode_matching** package offered facilities for generating plots of the field quantities along the symmetry planes of the waveguide antenna, only. Apart from this type of plots, the **Mode_matching_3D** package provides the possibility to generate plots of these quantities at planes that are parallel to the aperture's plane, hereafter referred to as "$z-$slice" plots. Note that these plots can also be employed for generating "movies".

For illustrating this feature, all three components of the quantities $\hat{\boldsymbol{E}}_2$ and $\hat{\boldsymbol{H}}_2$ are represented in Figs. 8 and 9, respectively, for the plane $z = 2.2\,10^{-4}\text{m} \approx 7.33\,10^{-4}\lambda_0$, with λ_0 denoting the wavelength in free-space corresponding to the exciting frequency (10GHz). In these figures, the singular behaviour of the field in the proximity of the aperture's edges is clearly visible. Note that, for being able to highlight this phenomenon, a number of 75 $TE-$ and 70 $TM-$modes were employed for expanding the field in the waveguide.

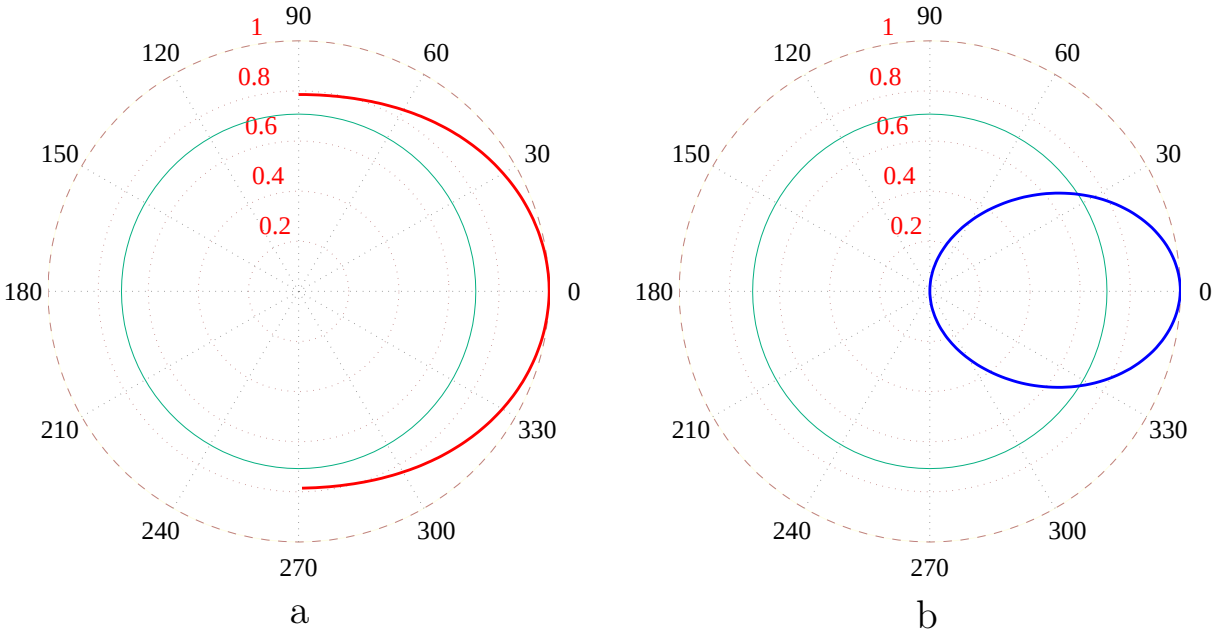

Figure 10: Radiation patterns for the co-polar component of the electric field's strength; the scale is linear. (a) $E-$plane; (b) $H-$plane.

Co- and cross-polar radiation patterns and plots

The previously available facilities for examining the propagation properties in the far-field region were broadened in the **Mode_matching_3D** package by adding options for generating plots of the co- and cross-polar components of the electric field's strength [5](p. 66) (these components being denoted as $\hat{E}^{\mathrm{co-pol}}_{2;\infty}$ and $\hat{E}^{\mathrm{cross-pol}}_{2;\infty}$, respectively). The following types of plots are hereafter presented:

- radiation patterns for the co-polar component of the electric field's strength in the $E-$ and $H-$planes (see Fig. 10),
- radiation patterns for both the co- and the cross-polar components of the electric field's strength [5](p. 66) in the $E-$ and $H-$planes (see Fig.) and
- radiation plots, illustrating the three-dimensional distribution of the co- and cross-polar components of the electric field's strength for the complete radiation hemisphere $\theta \in [0, \pi/2)$ and $\varphi \in [0, 2\pi)$ (see Fig.12).

Acknowledgement

The theoretical foundations of the reported results were laid during a four year cooperation with PROF.DR.IR. ADRIANUS T. DE HOOP. His constant support received during the development and testing of the software package is gratefully acknowledged. Acknowledgement is also due to ING. CRISTIAN COMAN for providing implementation solutions to some of the post-processing and user-interface features of the code.

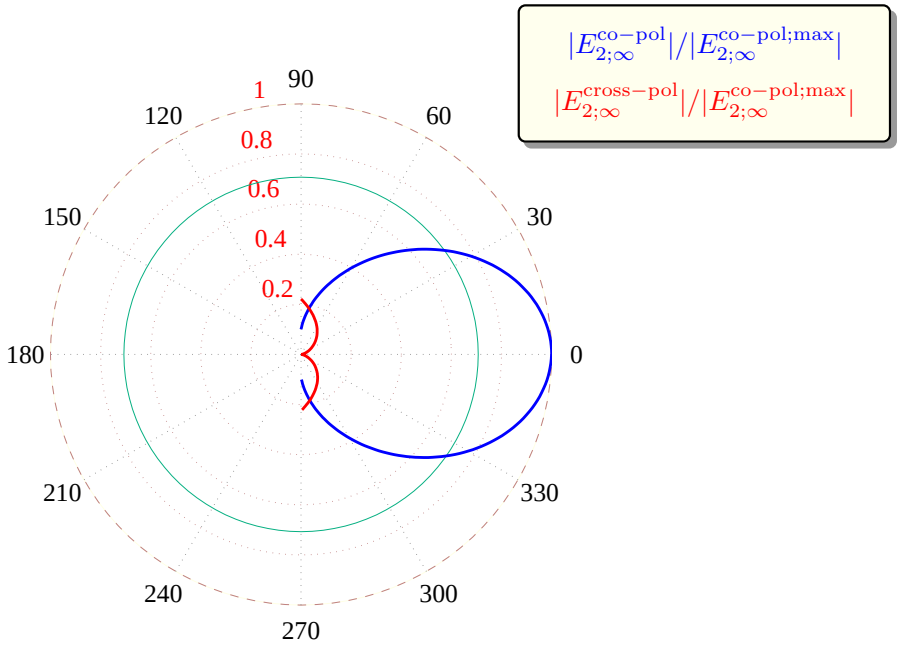

Figure 11: Radiation patterns for the co- and cross-polar components of the electric field's strength in a plane rotated at an angle $\varphi = 24.4°$ (corresponding to one of the diagonal planes of the aperture); the scale is linear.

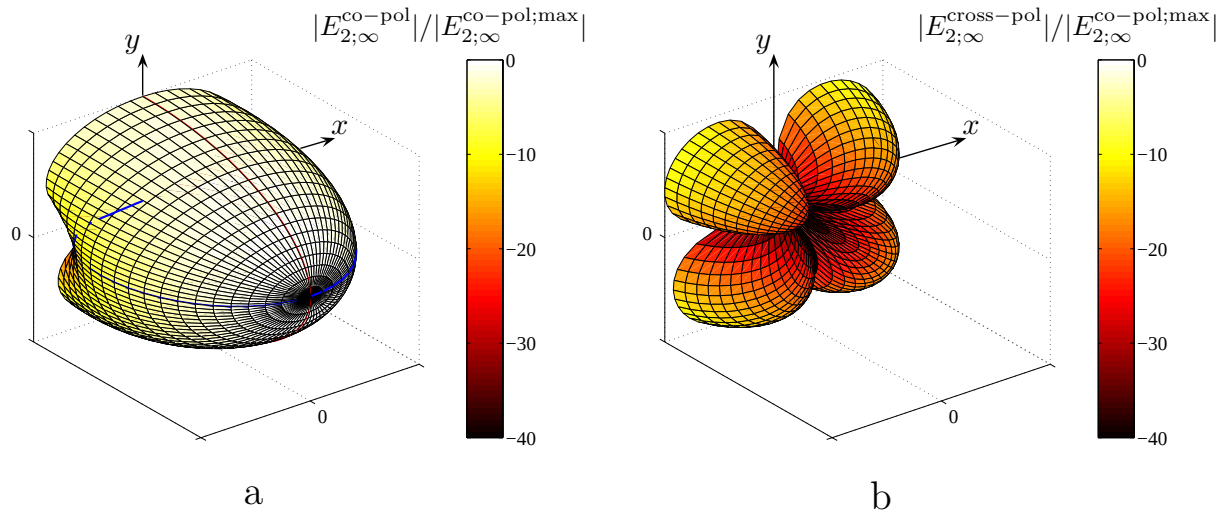

Figure 12: The components of the electric field's strength for the complete radiation hemisphere; the scale is logarithmic. (a) co-polar component; (b) cross-polar component.

A The list of functions implemented in the Mode_matching_3D software package

As mentioned in section 4.3, all input data for describing a (new) problem and/or for selecting the post-processing options must be included in an *input data file*. In this section, a complete list of the keywords recognised by the current version of the **Mode_matching_3D** software package is given. In this manner, the user can familiarise her or himself with the capabilities of the present version of this package.

A.1 General structure of the input file

The input data file is a standard ASCII file. For processing this file, appropriate *data parsers* have been incorporated in the **Mode_matching_3D** software package. For reasons of enhancing the flexibility of the manner in which the input data file can be prepared, the parsers are *case insensitive*. Nevertheless, for avoiding an excessive complication of the resulting code, the correctness and consistency checks carried out by the parsers *are minimal* and, hence, the user is expected to fully comply to the indications given in this "quick reference". Note that most (syntax) errors will result in an unpredictable behaviour of the program. However, the parsers will always check *the syntax of the keywords*, the occurrence of a keyword that does not belong to the program's "dictionary" resulting in stopping the program with an error message.

The structure of the input data file consists of *valid input lines* and, possibly, *comments*, as follows:

1. Valid input lines contain *keywords* and *parameters*. The keywords are grouped into two classes:

   - keywords that are used for describing the problem at hand (pre-processing keywords) and for overall program management,
   - keywords that are used for selecting post-processing options.

   The sequence of the keywords that belong to the same class is arbitrary. However, since the input data file parsers for the two classes are separate, keywords belonging to different classes *may not be mixed*.

2. Any text that follows after a "%" (CHR(37)) character is taken to be a comment and *is not interpreted*.

In view of enhancing the readability of the input data file, some text formatting options are accepted by the software package's parsers:

1. The file may contain *completely* blank lines. Note that including blank lines and comments between keywords and their pertaining parameters is permitted.

2. The valid input lines can be indented using BLANK (CHR(32)) characters. Note that the use of TAB (CHR(7)) characters for indentation should be avoided as it can result in an unpredictable behaviour of the parsers.

The complete list of keywords, together with their pertaining parameters, is presented hereafter. For reasons of consistency, the keywords are given in uppercase, only. Recall, however, that the parsers are case insensitive. As a general rule, the valid input lines have the format:

KeyWord
first line of parameter(s)
second line of parameter(s)
... line of parameter(s)

Note that parameters listed in this "quick reference" on one line *must* appear in the input data file on the same line.

A.2 Pre-processing keywords

The pre-processing keywords are used for defining the data concerning a (new) problem. All parameters that are prescribed by means of valid input described in this section have default values and, hence, the use of all these keywords is optional. However, most default values concern a trivial problem and, hence, these parameters should be explicitly defined by the user for any practical application.

Keywords employed for problem definition

MINIMUM NO OF MODES

Parameter:

- 1 integer (Minimum_No_Of_Modes) $\Longrightarrow$ the minimum number of $TE-$modes to be accounted for.

MINIMUM HIGHEST CUTOFF

Parameter:

- 1 integer (Minimum_Highest_Cutoff) $\Longrightarrow$ the minimum limit of the maximum cutoff frequency of the $TE-$ modes to be accounted for.

NOTES: The program effectively employs as number of $TE-$modes the larger value between the one that is specified by means of the **MINIMUM NO OF MODES** command and that that follows from the condition given by the **MINIMUM HIGHEST CUTOFF** command. For example, for the configuration indicated in Fig. 3, specifying a Minimum_Highest_Cutoff $= 200$ GHz will require a number of 75 $TE-$modes, that is larger than the specified Minimum_No_Of_Modes (6). Consequently, the program will employ a number of 75 $TE-$modes.

The number of $TM-$modes is automatically determined from the condition that the highest cutoff frequency of a $TM-$mode should not exceed the highest cutoff frequency of any $TE-$mode that is accounted for. Due to the $TM-$modes having a higher minimum cutoff frequency than that of the $TE-$modes, the program will always account for less $TM-$modes.

EXCITED MODES

Parameters:

- 1 integer (N_EXCITED_Modes) $\Longrightarrow$ the number of excited modes;
  fatal error when N_EXCITED_Modes exceeds the total ($TE-$ &$TM-$) modes;
  fatal error when the amplitude of an evanescent mode is prescribed,
- N_EXCITED_Modes *doublets* of real numbers, each on a separate line $\Longrightarrow$ the amplitude values of the excited modes, ordered according to their increasing cutoff frequency; in the case $TE-$ and $TM-$modes with the same frequency are prescribed, the amplitude of the $TE-$mode must be prescribed firstly.
  No consistency check is carried out.

FREQUENCY

Parameter:

- 1 real number (Frequency) $\Longrightarrow$ the frequency of the first $TE-$mode (the funadamental mode).
  When Frequency < 0, the frequency of the funadamental mode is chosen such that the wavelength λ_0 corresponding to this mode satisfies the condition $a = |\mathsf{frequency}|\,\lambda_0$, with a denoting the *necessarily prescribed* width of the waveguide (see Fig. 1).

WIDTH

Parameter:

- 1 real number (Width) $\Longrightarrow$ the width a of the waveguide (see Fig. 1)
  When Width < 0, the width of the waveguide is chosen such that $a = |\mathsf{Width}|\,\lambda_0$, with λ_0 denoting the wavelength corresponding to the *necessarily prescribed* frequency of the fundamental mode.

NOTE: Width and frequency *cannot* be negative at the same time. The value of at least one of them must be prescribed by the user.

HEIGHT

Parameter:

- 1 real number (Height) $\Longrightarrow$ the height b of the waveguide (see Fig. 1); *the dimension* Height *must be positive!*

FILLING

Parameters:

- 1 real number (mu_r_1) $\Longrightarrow$ the relative permeability of the medium in the waveguide ($\mu_{1;\mathrm{r}}$ – see section 2),
- 1 real number (eps_r_1) $\Longrightarrow$ the relative primitivity of the medium in the waveguide ($\varepsilon_{1;\mathrm{r}}$ – see section 2).

No checking of the input values is carried out.

EMBEDDING

Parameters:

- 1 real number (mu_r_2) $\Longrightarrow$ the relative permeability of the medium in the unbounded right half-space ($\mu_{2;\mathrm{r}}$ – see section 2),
- 1 real number (eps_r_2) $\Longrightarrow$ the relative primitivity of the medium in the unbounded right half-space ($\varepsilon_{2;\mathrm{r}}$ – see section 2).

No checking of the input values is carried out.

TRUNCATION ERROR AT INFINITY

Parameter:

- 1 real number (Inf_Truncation_Error) $\Longrightarrow$ the prescribed accuracy in the computation of the "infinite" integrals; Inf_Truncation_Error must be larger than 10^{-7} and it is typically chosen in the range $10^{-5}, \ldots, 10^{-6}$.

SOLUTION FILE NAME

Parameter:

- string (Solution_File_Name) $\Longrightarrow$ the name of the file, *without the full path and the extension*, where the solution of the problem is saved.

NOTE: The program fills in automatically the full path to the directory where the **Mode_matching_3D** output data files are located and the default extension `.sol`.

Keywords employed for the overall program management

RUN TYPE

Parameter:

- 1 integer (Run_Type) $\Longrightarrow$ parameter controlling the runtime operating mode of the program (see section 4.3).

DO SPECTRAL ANALYSIS

(No parameters)

The execution is switched over to the spectral analysis mode.

POST PROCESSING

(No parameters)

Beginning of the part of the input data file containing the data for post-processing.

NOTE: This keyword commutes the processing of the input data file to the parsers of the post-processing part, that do not recognise any problem definition (pre-processing) keywords. As a consequence, no such keywords may occur after the **POST PROCESSING** keyword.

END

(No parameters)

The end of the input data file.

NOTE: This keyword is recognised by the parsers of the post-processing part of the input data file, as well.

A.3 Post-processing keywords

The post-processing keywords are used for selecting the post-processing options. The use of all keywords listed in this section is optional.

Keywords employed for console output

COMPUTE GAIN 0

(No parameters)

Compute the gain of the aperture for $\theta = 0^\circ$ (see Section 2).

COMPUTE GAIN

Parameters:

- 2 real numbers (Theta and Phi) $\Longrightarrow$ the direction angles θ and φ (see Section 2), in degrees.

Compute the gain of the aperture for the direction defined by $\theta = \mathsf{Theta}^\circ$ and $\varphi = \mathsf{Phi}^\circ$.

COMPUTE DIRECTIVITY 0

(No parameters)

Compute the directivity of the aperture for $\theta = 0^\circ$ (see Section 2).

COMPUTE DIRECTIVITY

Parameters:

- 2 real numbers (Theta and Phi) $\Longrightarrow$ the direction angles θ and φ (see Section 2), in degrees.

Compute the directivity of the aperture for the direction defined by $\theta = \mathsf{Theta}^\circ$ and $\varphi = \mathsf{Phi}^\circ$.

COMPUTE TL-PARAMETERS TE_10

(No parameters)

Compute the tramsmission line parameters of the aperture, i.e. the S_{11} parameter (magnitude and phase) and the VSWR, for the $TE_{10}-$mode.

COMPUTE TL-PARAMETERS TE-MODE

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TE-$mode that is accounted for.

Compute the tramsmission line parameters of the aperture, i.e. the S_{11} parameter (magnitude and phase) and the VSWR, for the $TE_{MN}-$mode.

COMPUTE TL-PARAMETERS TM-MODE

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TM-$mode that is accounted for.

Compute the tramsmission line parameters of the aperture, i.e. the S_{11} parameter (magnitude and phase) and the VSWR, for the $TM_{MN}-$mode.

Keywords employed for setting aspect parameters of the generated plots

PLOT ANGLE

Parameter:

- 1 integer (Angle) $\Longrightarrow$ the viewing angle to be used in the case of "(lighted) surface" plots, in multiples of 90°.

No checking of the input values is carried out.

SHADING TYPE

Parameter:

- 1 integer (Shading_Type) $\Longrightarrow$ flag that controls the shading type to be used in the case of "(lighted) surface" plots.

NOTE: The following values of Shading_Type are accepted:

- 0 $\Longrightarrow$ shading flat,
- 1 $\Longrightarrow$ shading facetted (default).

Invalid values are converted to the default one (1).

DISPLAY TEXT

Parameter:

- 1 integer (Display_text) $\Longrightarrow$ flag that controls the displaying of the titles in all kind of plots.

NOTE: The following values of Display_text are accepted:

- 0 $\Longrightarrow$ do not display titles,
- 1 $\Longrightarrow$ display titles (default).

Invalid values are converted to the default one (1).

DISPLAY COLORBAR

Parameter:

- 1 integer (Display_colorbar) $\Longrightarrow$ flag that controls the displaying of the colorbar in "filled contour" type plots (generated by means of the the MATLAB "conturf" function).

NOTE: The following values of Display_colorbar are accepted:

- 0 $\Longrightarrow$ do not display the colorbar,
- 1 $\Longrightarrow$ display the colorbars (default).

Invalid values are converted to the default one (1).

FONT SIZES

Parameters:

- 2 integers (FontSize and NotationFontSize) $\Longrightarrow$ the font sizes, in points, to be used in all kind of plots; FontSize is used for rendering the titles and the axes' labels and NotationFontSize is used for rendering the axes' notations.

Invalid values (i.e. negative ones) are converted to the default font sizes (10 pt).

APERTURE DISTRIBUTION STEP RATIO

Parameter:

- 1 real (Step_ratio) $\Longrightarrow$ the ratio at which the steps of the non-uniform grids employed for generating plots are increased.

NOTE: By default, two- and (pseudo-) three-dimensional plots are generated using a uniform mesh. Nevertheless, it is often convenient to generate these plots for a non-uniform grid, having a maximum density in the vicinity of the edges of the waveguide's aperture and being increasingly coarser when moving away from them. The accepted values of the Step_ratio parameter are Step_ratio $\geqslant 1$ and invalid values (Step_ratio < 1) are converted to the default one (1). Note that experience has shown that the aspect of the generated plots tends to deteriorate significantly when Step_ratio exceeds $1.2 \ldots 1.3$.

Keywords employed for the analysis of propagation properties in the far-field region

RADIATION PATTERN *or* FAR-FIELD PATTERN (obsolete)

Parameters:

- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, where the far-field is computed,
- 1 real number (Increment) $\Longrightarrow$ the minimum level, in deciBells, which is represented in the case of the logarithmic plot.

No checking of the input values is carried out.

Generates the radiation patterns for $\theta = 0°, \ldots, 90°$ in the $E-$ and $H-$planes, at both a linear and a logarithmic scale.

RADIATION PATTERN DB *or*
FAR-FIELD PATTERN DB (obsolete)

Parameters:

- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, where the far-field is computed,
- 1 real number (Increment) $\Longrightarrow$ the minimum level, in deciBells, which is represented.

No checking of the input values is carried out.

Generates the radiation patterns for $\theta = 0°, \ldots, 90°$ in the $E-$ and $H-$planes, at a logarithmic scale.

RADIATION PATTERN LINEAR *or*
FAR-FIELD PATTERN LINEAR (obsolete)

Parameter:

- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, where the far-field is computed.

No checking of the input values is carried out.

Generates the radiation patterns for $\theta = 0°, \ldots, 90°$ in the $E-$ and $H-$planes, at a linear scale.

POLARISATION PATTERN

Parameters:

- 1 real number (Phi) $\Longrightarrow$ the rotation angle φ (see Section 2), in degrees,
- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, where the far-field is computed,
- 1 real number (Increment) $\Longrightarrow$ the minimum level, in deciBells, which is represented in the case of the logarithmic plot.

No checking of the input values is carried out.

Generates the co- and cross-polar radiation patterns for $\theta = 0°, \ldots, 90°$ and for a specified rotation angle $\varphi =$ Phi°, at both a linear and a logarithmic scale.

POLARISATION PATTERN DB

Parameters:

- 1 real number (Phi) $\Longrightarrow$ the rotation angle φ (see Section 2), in degrees,
- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, where the far-field is computed,
- 1 real number (Increment) $\Longrightarrow$ the minimum level, in deciBells, which is represented.

No checking of the input values is carried out.

Generates the co- and cross-polar radiation patterns for $\theta = 0°, \ldots, 90°$ and for a specified rotation angle $\varphi =$ Phi°, at a logarithmic scale.

POLARISATION PATTERN LINEAR

Parameters:

- 1 real number (Phi) $\Longrightarrow$ the rotation angle φ (see Section 2), in degrees,
- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, where the far-field is computed.

No checking of the input values is carried out.

Generates the co- and cross-polar radiation patterns for $\theta = 0°, \ldots, 90°$ and for a specified rotation angle $\varphi =$ Phi°, at a linear scale.

RADIATION PLOT

Parameters:

- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, for both θ and φ, where the far-field is computed,
- 1 real number (Increment) $\Longrightarrow$ the minimum level, in deciBells, which is represented in the case of the logarithmic plot.

No checking of the input values is carried out.

Generates the co- and cross-polar radiation patterns for the complete radiation hemisphere $\theta = 0°, \ldots, 90°$ and $\varphi = 0°, \ldots, 360°$, at both a linear and a logarithmic scale.

RADIATION PLOT DB

Parameters:

- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, for both θ and φ, where the far-field is computed,
- 1 real number (Increment) $\Longrightarrow$ the minimum level, in deciBells, which is represented.

No checking of the input values is carried out.

Generates the co- and cross-polar radiation patterns for the complete radiation hemisphere $\theta = 0°, \ldots, 90°$ and $\varphi = 0°, \ldots, 360°$, at a logarithmic scale.

RADIATION PLOT LINEAR

Parameter:

- 1 integer (Density) $\Longrightarrow$ the number of points, per 90°, for both θ and φ, where the far-field is computed.

No checking of the input values is carried out.

Generates the co- and cross-polar radiation patterns for the complete radiation hemisphere $\theta = 0°, \ldots, 90°$ and $\varphi = 0°, \ldots, 360°$, at both a linear scale.

Keywords employed for generating two-dimensional plots

LINE APERTURE E_Y

Two-dimensional plots of the field quantities $\hat{E}_y(0, y, z_0)$ ($E-$plane) and $\hat{E}_y(x, 0, z_0)$ ($H-$plane) for a specified, *fixed*, z_0 coordinate, colour version. The employed mesh may be uniform or non-uniform. (This type of plots are, usually, generated for analysing the field distribution in the vicinity of the radiating aperture.)

Parameters:

- 2 real numbers (Z_Shift and Div_lambda_z) $\Longrightarrow$ the fixed z_0 coordinate for which the plot is generated, in multiples of the waveguide's width a (see Fig. 1), and the (minimum) size of the discretisation mesh step in the $\mathcal{O}y$ direction ($E-$plane) and in the $\mathcal{O}x$ direction ($H-$plane), in quotients of a,
- 1 integer (Which_Type) $\Longrightarrow$ parameter indicating which type of plot must be generated.

NOTES: The specified field quantity is plotted along the segments $\{x = 0\,,\, y \in [-1.5\,a\,,\, 1.5\,a\,]\,,\, z = \text{Z\_Shift}\,a\}$ ($E-$plane) and $\{x \in [-1.5\,a\,,\, 1.5\,a\,]\,,\, y = 0\,,\, z = \text{Z\_Shift}\,a\}$ ($H-$plane).
The following values of Which_Type are accepted:

- $1 \Longrightarrow \Re\left\{\hat{E}_y\right\}$ and $\Im\left\{\hat{E}_y\right\}$ (linear representation),
- $2 \Longrightarrow \Re\left\{\hat{E}_y\right\} / \left|\hat{E}_y\right|_{\max}$ and $\Im\left\{\hat{E}_y\right\} / \left|\hat{E}_y\right|_{\max}$ (linear representation),
- $3 \Longrightarrow \left|\hat{E}_y\right| / \left|\hat{E}_y\right|_{\max}$ and $\arg\left(\hat{E}_y\right)$ (linear representation).

By replacing in the definition above **E_Y** by **E_Z**, **H_X** or **H_Z**, similar plots for the field quantities $\hat{E}_z(x, z)$, $\hat{H}_x(x, z)$ or $\hat{H}_z(x, z)$, respectively, can be generated.

Keywords employed for generating (pseudo-) three-dimensional plots

NEAR-FIELD E_Y LIGHTED SURFACE

"Lighted surface" three-dimensional plots [11] of the field quantities $\hat{E}_{2;y}(0, y, z)$ ($E-$plane) and $\hat{E}_{2;y}(x, 0, z)$ ($H-$plane) in the vicinity of the radiating aperture *outside the waveguide, only*, colour version. For simplicity, the subsequent definitions refer to the $H-$plane, only, the definitions pertaining to the $E-$plane following by swapping x and y. Note that, in the following, λ_{emb} denotes the wavelength in the unbounded right-hand half-space (the embedding), for the prescribed frequency of the fundamental mode.

Parameters:

- 2 real numbers (Mult_lambda_z and Div_lambda_z) $\Longrightarrow$ the width of the plotted area (see Fig. 13), in multiples of λ_{emb}, and the size of the (minimum) discretisation mesh step in the $\mathcal{O}z$ direction, in quotients of λ_{emb},
- 2 real numbers (Mult_lambda_x and Div_lambda_x) $\Longrightarrow$ the height of the plotted area (see Fig. 13), in multiples of λ_{emb}, and the (minimum) size of the discretisation mesh step in the $\mathcal{O}x$ direction, in quotients of λ_{emb},
- 1 integer (Which_Type) $\Longrightarrow$ parameter indicating which type of plot must be generated.

NOTES: The ploted area is symmetrical with respect to the $\mathcal{O}x$ axis; the ploted area corresponds to the rectangle $[\,-\text{Mult\_lambda\_x}\,\lambda_{\text{emb}}\,,\,\text{Mult\_lambda\_x}\,\lambda_{\text{emb}}\,]\times[\,0\,,\,\text{Mult\_lambda\_z}\,\lambda_{\text{emb}}\,]$ and $y = 0$.
The following values of Which_Type are accepted:

- $1 \Longrightarrow \Re\left\{\hat{E}_{2;y}\right\}$ and $\Im\left\{\hat{E}_{2;y}\right\}$ (linear representation),
- $2 \Longrightarrow \Re\left\{\hat{E}_{2;y}\right\} / \left|\hat{E}_{2;y}\right|_{\max}$ and $\Im\left\{\hat{E}_{2;y}\right\} / \left|\hat{E}_{2;y}\right|_{\max}$ (linear representation),
- $3 \Longrightarrow \left|\hat{E}_{2;y}\right| / \left|\hat{E}_{2;y}\right|_{\max}$ and $\arg\left(\hat{E}_{2;y}\right)$ (linear representation),
- $4 \Longrightarrow \left|\hat{E}_{2;y}\right| / \left|\hat{E}_{2;y}\right|_{\max}$ (linear representation) and $\left|\hat{E}_{2;y}\right| / \left|\hat{E}_{2;y}\right|_{\max}$, (logarithmic representation).

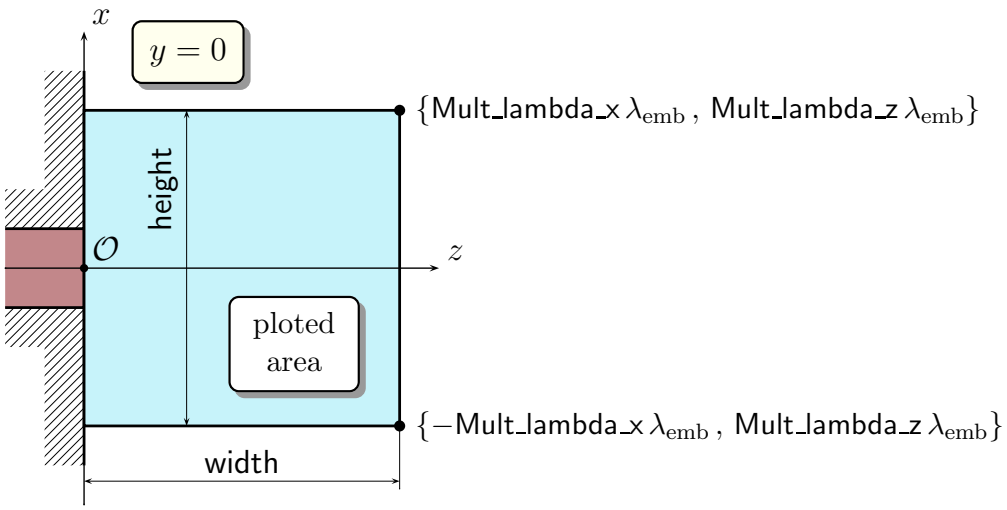

Figure 13: The dimensions of the plotted area in the case of "near-field" type plots ($H-$plane).

NEAR-FIELD E_Y LIGHTED SURFACE B/W

Same as **NEAR-FIELD E_Y LIGHTED SURFACE**, black and white version.

NEAR-FIELD E_Y SURFACE

Same as **NEAR-FIELD E_Y LIGHTED SURFACE**, "shaded surface" three-dimensional plots [11], colour version.

NEAR-FIELD E_Y SURFACE B/W

Same as **NEAR-FIELD E_Y SURFACE**, black and white version.

NEAR-FIELD E_Y CONTOURF

Same as **NEAR-FIELD E_Y LIGHTED SURFACE**, "filled contour" pseudo-three-dimensional plots ("conturf" [11]), colour version.

NEAR-FIELD E_Y CONTOURF B/W

Same as **NEAR-FIELD E_Y CONTOURF**, black and white version.

By replacing in the definitions above **E_Y** by **E_Z**, **H_X** or **H_Z**, similar types of plots for the field quantities $\hat{E}_{2;z}(x,z)$, $\hat{H}_{2;x}(x,z)$ or $\hat{H}_{2;z}(x,z)$, respectively, can be generated.

APERTURE E_Y LIGHTED SURFACE

"Lighted surface" three-dimensional plots of the field quantities $\hat{E}_y(0,y,z)$ ($E-$plane) and $\hat{E}_y(x,0,z)$ ($H-$plane) in the vicinity of the radiating aperture *both inside and outside the waveguide*, colour version. For simplicity, the subsequent definitions refer to the $H-$plane, only, the definitions pertaining to the $E-$plane following by swapping x and y.

Parameters:

- 2 real numbers (Mult_Width_z and Div_Width) $\Longrightarrow$ the length of the represented domain inside the waveguide, in multiples of its width a (see Fig. 14) and the size of the (minimum) representation mesh step in both directions, in quotients of a,
- 1 integer (Which_Type) $\Longrightarrow$ parameter indicating which type of plot must be generated.

NOTES: The ploted area is symmetrical with respect to the $\mathcal{O}x$ axis; the ploted area corresponds to the rectangle $[\,-1.5\,a\,,\,1.5\,a\,]\times[\,-$Mult_lambda_z $a\,,\,2\,a\,]$ and $y=0$, the areas delimited by the surfaces of the perfectly conducting shield and flanges being clipped out.

NOTES: The following values of Which_Type are accepted:

- $1 \Longrightarrow \Re\left\{\hat{E}_y\right\}$ and $\Im\left\{\hat{E}_y\right\}$ (linear representation),
- $2 \Longrightarrow \Re\left\{\hat{E}_y\right\} / \left|\hat{E}_y\right|_{\max}$ and $\Im\left\{\hat{E}_y\right\} / \left|\hat{E}_y\right|_{\max}$ (linear representation),
- $3 \Longrightarrow \left|\hat{E}_y\right| / \left|\hat{E}_y\right|_{\max}$ and $\arg\left(\hat{E}_y\right)$ (linear representation),
- $4 \Longrightarrow \left|\hat{E}_y\right| / \left|\hat{E}_y\right|_{\max}$ (linear representation) and $\left|\hat{E}_y\right| / \left|\hat{E}_y\right|_{\max}$, (logarithmic representation).

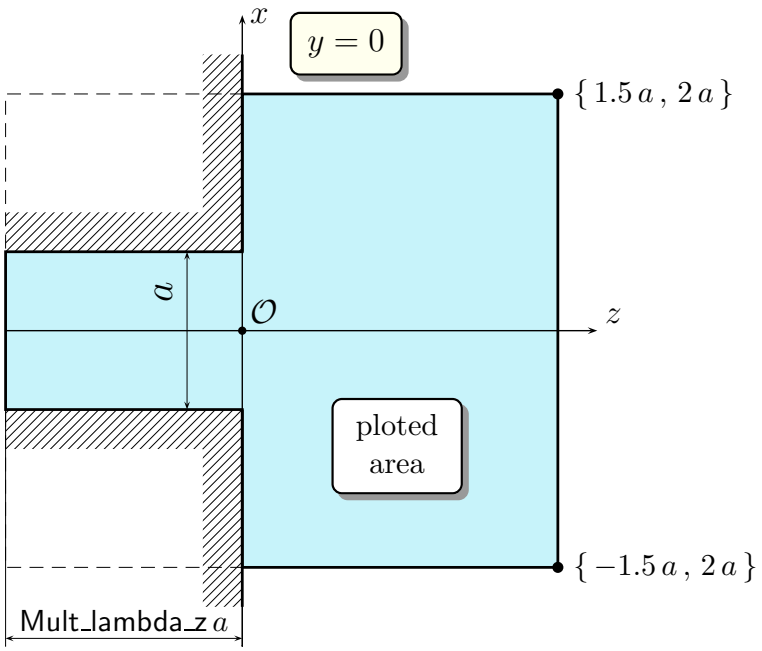

Figure 14: The dimensions of the plotted area in the case of "aperture" type plots ($H-$plane).

APERTURE E_Y LIGHTED SURFACE B/W

Same as **APERTURE E_Y LIGHTED SURFACE**, black and white version.

APERTURE E_Y SURFACE

Same as **APERTURE E_Y LIGHTED SURFACE**, "shaded surface" three-dimensional plots, colour version.

APERTURE E_Y SURFACE B/W

Same as **APERTURE E_Y SURFACE**, black and white version.

APERTURE E_Y CONTOURF

Same as **APERTURE E_Y LIGHTED SURFACE**, "filled contour" pseudo-three-dimensional plots, colour version.

APERTURE E_Y CONTOURF B/W

Same as **APERTURE E_Y CONTOURF**, black and white version.

By replacing in the definitions above **E_Y** by **E_Z**, **H_X** or **H_Z**, similar types of plots for the field quantities $\hat{E}_z(x,z)$, $\hat{H}_x(x,z)$ or $\hat{H}_z(x,z)$, respectively, can be generated.

SLICE LIGHTED SURFACE

"Lighted surface" three-dimensional plots of the field quantities $\hat{E}_x(x,y,z_0)$, $\hat{E}_y(x,y,z_0)$, $\hat{E}_z(x,y,z_0)$, $\hat{H}_x(x,y,z_0)$, $\hat{H}_y(x,y,z_0)$ or $\hat{H}_z(x,y,z_0)$ for a plane $\{z = z_0\}$ that is parallel to the aperture's plane ("z-slice" plots).

Parameters:

- 1 integer (Which_Quantity) $\Longrightarrow$ parameter indicating which field quantity must be represented,
- 2 real numbers (Mult_WGdims and Div_WGdims) $\Longrightarrow$ the dimensions of the plotted area, in multiples of the waveguide's width a and height b, and the size of the (minimum) representation mesh step in the $\mathcal{O}x$ and $\mathcal{O}y$ directions, in quotients of a and b, respectively,
- 1 real (Z_shift) $\Longrightarrow$ the value of the constant z_0 parameter, in multiples of a,
- 1 integer (Which_Type) $\Longrightarrow$ parameter indicating which type of plot must be generated.

NOTES: The ploted area is symmetrical with respect to the $\mathcal{O}x$ and $\mathcal{O}y$ axes; the ploted area corresponds to the rectangle $[\,-\mathsf{Mult\_WGdims}\,a\,,\,\mathsf{Mult\_WGdims}\,a\,]\times[\,-\mathsf{Mult\_WGdims}\,b\,,\,\mathsf{Mult\_WGdims}\,b\,]$.

The following values of Which_Type are accepted:

- $1 \Longrightarrow \hat{E}_x(x,y,z_0)$,
- $2 \Longrightarrow \hat{E}_y(x,y,z_0)$,
- $3 \Longrightarrow \hat{E}_z(x,y,z_0)$,
- $11 \Longrightarrow \hat{H}_x(x,y,z_0)$,
- $12 \Longrightarrow \hat{H}_y(x,y,z_0)$,
- $13 \Longrightarrow \hat{H}_z(x,y,z_0)$.

Attempting to prescribe a different value of the Which_Type parameter will be signaled as an error and will result in the command being ignored.

The following values of Which_Type are accepted:

- $1 \Longrightarrow \Re\left\{\hat{E}_y\right\}$ and $\Im\left\{\hat{E}_y\right\}$ (linear representation),
- $2 \Longrightarrow \Re\left\{\hat{E}_y\right\} / \left|\hat{E}_y\right|_{\max}$ and $\Im\left\{\hat{E}_y\right\} / \left|\hat{E}_y\right|_{\max}$ (linear representation),
- $3 \Longrightarrow \left|\hat{E}_y\right| / \left|\hat{E}_y\right|_{\max}$ and $\arg\left(\hat{E}_y\right)$ (linear representation),
- $4 \Longrightarrow \left|\hat{E}_y\right| / \left|\hat{E}_y\right|_{\max}$ (linear representation) and $\left|\hat{E}_y\right| / \left|\hat{E}_y\right|_{\max}$, (logarithmic representation).

SLICE LIGHTED SURFACE B/W

Same as **SLICE LIGHTED SURFACE**, black and white version.

SLICE SURFACE

Same as **SLICE LIGHTED SURFACE**, "shaded surface" three-dimensional plots, colour version.

SLICE SURFACE B/W

Same as **SLICE SURFACE**, black and white version.

SLICE CONTOURF

Same as **SLICE LIGHTED SURFACE**, "filled contour" pseudo-three-dimensional plots, colour version.

SLICE CONTOURF B/W

Same as **SLICE CONTOURF**, black and white version.

Keywords employed for generating two– and (pseudo-) three-dimensional "movies"

For visualising transient phenomena, the **Mode_matching_3D** software package contains an option for generating a sequence of "frames" (snapshots of the distribution of the field quantities at successive instants) that can subsequently be "played-back" as a "movie" [11]. For generating "movies", any of the plot types mentioned above may be employed.

MOVIE

Generate the frames for a "movie" using one of the types of plots described above.

Parameters:

- 2 integers (Time_Divisions and Repeat) $\Longrightarrow$ the number of intervals one period of the first prescribed mode is divided into and the number of times the sequence of frames is repeated during the "movie".

NOTE: The "movies" are generated using any of the types of two- and (pseudo-) three-dimensional plots mentioned above. Consequently, the declaration of the "movie" parameters *must* be followed by a valid definition of a two- or (pseudo-) three-dimensional plot. Any other post-processing keyword will be ignored by the "movie" parser. This will result, most likely, in a syntax error that will be detected at the first subsequent, non-comment, input line.

MAKE THE MOVIE

(No parameters)

Keyword used for marking the end of the input data to be used for the generation of "movies".

NOTE: This keyword may be skipped, if the movie declaration is ended by the keyword **END** (the end of input data).

The **Mode_matching_3D** package offers the possibility to save a generated movie into an external "mat" file [10] that can be subsequently loaded into the MATLAB environment and played-back. In the case when MATLAB version 6.0 (or higher) is available, the generated movie can be saved into an external *Audio/visual interleaved* (avi) file, as well. The user is prompted to indicate which of the generated "movies" should be saved, in what format. Subsequently, the name of the output file *without extension* (the required extension being appended by the program) must be provided. The "movie" files are saved in the <`home_directory`>\`Matlab_movies` directory (see section 4.1). The user may indicate the path to subdirectories of this directory, *providing that these subdirectories exist.*

For playing-back of a "movie" saved as a "mat" file, it is recommended to use the MATLAB module `play_saved_movie.m` that is provided with the package. It should be taken into account that the saved "movie" files are often extremely large (typically, tens of megabytes).

From this point of view, saving a "movie" as an "avi" file represents a considerably more convenient solution. In this manner, a compression factor of 20 (or larger) is often obtained, with a negligible loss of picture quality. The generated "avi" files can then be played-back with any standard **Microsoft Windows** software (such as **Microsoft Media Player**) and are amenable to be included in **Microsoft Power-Point** presentations.

A.4 Spectral analysis keywords

The keywords pertaining to the spectral analysis module of the **Mode_matching_3D** code are grouped into three classes:

- keywords that are used for describing the problem at hand (pre-processing keywords),
- keywords that are used for overall program management (activation of the spectral analysis module itself and of the pertaining post-processing options),
- keywords that are used for selecting post-processing options.

Except for the keywords in the second class, the sequence of the keywords that belong to the same class is arbitrary. Since the input data file parsers for the three classes are separate, keywords

belonging to different classes *may not be mixed*. In view of ensuring the consistency of the input referring to this module with that employed by the single frequency one, the keywords in the second and the third classes *may appear after the* **POST PROCESSING** *command, only*. On the other hand, the keywords in the first class are accepted by the pre-processing parser *even in the single frequency operating mode*. When encountered, their pertaining parameters are simply ignored, without causing any error.

The user is warned that, after entering a sequence of spectral analysis related post-processing commands, the single frequency specific post-processing keywords are not recognised anymore. Consequently, it is the user's responsibility to close the relevant sequence with an **END** command (or by the end of the file), thus stopping the execution of the program.

The three classes of keywords recognised by the parsers of the spectral analysis module are hereafter examined separately.

Keywords employed for describing the problem at hand

These keywords are used for defining the data concerning a (new) problem. All parameters that are prescribed by means of valid input described in this section have default values and, hence, the use of the keywords listed in this section is optional. However, most default values concern a trivial problem and, hence, for all practical applications, these parameters should be explicitly defined by the user.

SPECTRAL FREQUENCY RANGE

Parameters:

- 2 real numbers (low_frequency and high_frequency) $\Longrightarrow$ the lower and upper bounds of the frequency range to be investigated.

SPECTRAL SAMPLING FREQUENCIES

Parameter:

- 1 real number (N_tot_f) $\Longrightarrow$ the number of frequency samples along the frequency range to be investigated.

DECREASING SAMPLING STEPS

(No parameters)

Flag indicating that the frequency range is sampled at *logarithmically decreasing* steps.

CONSTANT SAMPLING STEPS

(No parameters)

Flag indicating that the frequency range is sampled at *constant* steps.

INCREASING SAMPLING STEPS

(No parameters)

Flag indicating that the frequency range is sampled at *logarithmically increasing* steps.

SPECTRAL SOLUTION FILE NAME

Parameter:

- string (s_a_Solution_File_Name) $\Longrightarrow$ the name of the file, *without the full path and the extension*, where the solution of the problem is saved.

NOTE: The program fills in automatically the full path to the directory where the **Mode_matching_3D** output data files are located and the default extension `.sol`.

Keywords employed for the overall program management

The program management keywords indicate the beginning of a sequence of post-processing commands that are specific to the spectral analysis module. Recall that these keywords may appear after the **POST PROCESSING** keyword, only.

POST PROCESS / SPECTRAL ANALYSIS

(No parameters)

Activates the search for spectral analysis module related post-processing commands.

NOTE: After this keyword, spectral analysis module related post-processing commands may appear, only.

END

(No parameters)

The end of input data file.

NOTE: This keyword is recognised by the parser of the post-processing part of the input data file, as well.

Keywords employed for selecting the post-processing options

The post-processing keywords are used for selecting the post-processing options. The use of all keywords listed in this section is optional.

REVERT HARDCOPY

(No parameters)

Revert the plot during printout. Note that most spectral analysis related plots have a dark background.

UNCHANGED HARDCOPY

(No parameters)

Leave the plot unchanged during printout.

PLOT GAIN

(No parameters)

Plot the gain of the aperture for $\theta = 0°$ (see Section 2).

PLOT SCALED GAIN

Parameter:

- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the gain of the aperture for $\theta = 0°$, scaled down by the one corresponding to the frequency Ref_freq.

PLOT DIRECTIVITY

(No parameters)

Plot the directivity of the aperture for $\theta = 0°$.

PLOT SCALED DIRECTIVITY

Parameter:

- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the directivity of the aperture for $\theta = 0°$, scaled down by the one corresponding to the frequency Ref_freq.

PLOT S_11 TE_10

(No parameters)

Plot the S_{11} parameter (magnitude and phase) for the $TE_{10}-$mode.

PLOT SCALED S_11 TE_10

Parameter:

- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the S_{11} parameter (magnitude and phase) for the $TE_{10}-$mode, the magnitude being scaled down by the one corresponding to the frequency Ref_freq.

PLOT S_11 TE_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TE-$mode that is accounted for.

Plot the S_{11} parameter (magnitude and phase) for the $TE_{MN}-$mode.

PLOT SCALED S_11 TE_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TE-$mode that is accounted for.
- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the S_{11} parameter (magnitude and phase) for the $TE_{MN}-$mode, the magnitude being scaled down by the one corresponding to the frequency Ref_freq.

PLOT S_11 TM_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TM-$mode that is accounted for.

Plot the S_{11} parameter (magnitude and phase) for the $TM_{MN}-$mode.

PLOT SCALED S_11 TM_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TM-$mode that is accounted for.
- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the S_{11} parameter (magnitude and phase) for the $TM_{MN}-$mode, the magnitude being scaled down by the one corresponding to the frequency Ref_freq.

PLOT VSWR TE_10

(No parameters)

Plot the voltage standing wave ratio (VSWR) for the $TE_{10}-$mode.

PLOT SCALED VSWR TE_10

Parameter:

- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the VSWR for the $TE_{10}-$mode, scaled down by the one corresponding to the frequency Ref_freq.

PLOT VSWR TE_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TE-$mode that is accounted for.

Plot the VSWR for the $TE_{MN}-$mode.

PLOT SCALED VSWR TE_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TE-$mode that is accounted for.
- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the VSWR for the $TE_{MN}-$mode, scaled down by the one corresponding to the frequency Ref_freq.

PLOT VSWR TM_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TM-$mode that is accounted for.

Plot the VSWR for the $TM_{MN}-$mode.

PLOT SCALED VSWR TM_MN

Parameters:

- 2 integer numbers (M and N) $\Longrightarrow$ the indices of a $TM-$mode that is accounted for.
- 1 real number (Ref_freq) $\Longrightarrow$ reference frequency.

Plot the VSWR for the $TM_{MN}-$mode, scaled down by the one corresponding to the frequency Ref_freq.

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